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Research article

The use of smart technologies in enabling construction components reuse: A viable method or a problem creating solution?

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A R T I C L E I N F O

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A B S T R A C T

The exploitation of Radio Frequency Identification (RFID) for tracking and archiving the properties of structural construction components could be a potentially innovative disruption for the construction sector. This is because RFID can stimulate the reuse of construction components and reduce their wastage, hence addressing sustainability issues in the construction sector. To test the plausibility of that idea, this study explores the potential pre-conditions for RFID to facilitate construction components reuse, and develops a guidance for promoting their redistribution back to the supply chain. It also looks at how integrating RFID with Building Information Modelling (BIM) can possibly be a valuable extension of its capabilities, providing the opportunity for tracked components to be incorporated into new structures in an informed, sound way. A preliminary assessment of the strengths, weaknesses, opportunities and threats of the RFID technology is presented in order to depict its current and future potential in promoting construction components' sustainable lifecycle management, while emphasis has been laid on capturing their technical, environmental, economic and social value. Findings suggest that the collection of the right amount of information at the design-construction-deconstruction-reuse-disposal stage is crucial for RFID to become a successful innovation in the construction sector. Although a number of limitations related to the technical operability and recycling of RFID tags seem to currently hinder its uptake for structural components' lifecycle management, future technological innovations could provide solutions that would enable it to become a mainstream practice. Taken together these proposals advocate that the use of RFID and its integration with BIM can create the right environment for the development of new business models focused on sustainable resource management. These models may then unlock multiple values that are otherwise dissipated in the system. If the rapid technological development of RFID capability can be allied to policy interventions that control and manage its uptake along the supply chain, the sustainable lifecycle management of construction components could be radically enhanced.

1. Introduction

Construction and demolition waste (CDW) constitutes one third of the total solid waste generated in Europe, accounting for over 800m tonnes of waste generated per year (European Commission, 2016b). The high potential for reusing and recycling the multiple components/materials of which CDW is comprised, coupled with the need to close the material loops and move towards a circular economy, has led to categorisation of CDW by the European Commission as a priority waste stream (BIO Intelligence Service, 2011; European Commission, 2016a). This has urged the construction sector to introduce sustainable practices that seek to support and promote efficiency associated with the production of various construction components (e.g. fabricated pipes, structural steel members, precast concrete blocks, etc.), their use, end-of-use (EoU) and end-of-life (EoL) management (Iacovidou and Purnell, 2016). Although recycling of CDW is considered to be an established process for the CDW management (mainly driven by the requirement to divert it from landfill and only minimally by the recovery of technically or economically valuable material), the recovery of the structural or functional value of construction components via reuse has been largely overlooked.

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Reuse is recognised by the European Commission as a better practice in the construction sector as it promotes higher recovery of value as opposed to recycling (European Commission, 2016a). A number of design interventions that can stimulate the reuse of construction components have thus been widely documented in the global literature and recently reviewed (Iacovidou and Purnell, 2016). These interventions - adaptive reuse, deconstruction, design for deconstruction (DfD), design for reuse (DfR) and design for manufacture and assembly (DfMA) - have many benefits to offer. Short-term economic and organisational factors, as well as technical constraints associated with the identification, recovery and handling of construction components currently impede the realisation of these benefits (Iacovidou and Purnell, 2016). This is largely attributed to the lack of information regarding the lifespan of construction components; transformation of their physical and technical characteristics over their service life; and the options available for optimising the recovery of their value at their EoL stage, all of which make the implementation of such interventions and/or the recovery of construction components from CDW a real challenge.

Present design practices focus on initially documenting a relatively small subset of nominal 'upstream' technical properties for a given construction component, e.g. strength, stiffness, generic durability class and financial cost. Between this subset of properties and the additional 'downstream' properties required to promote reuse of components, e.g. the exposure and loading history of the component, its connection details, and the likely lifespan of the component (Iacovidou and Purnell, 2016), there is a knowledge gap that needs to be filled. Issues regarding the documentation, archiving and updating of 'upstream' and 'downstream' data, which may only exist in initial inventories and CAD drawings, and whose transfer to subsequent owners and operators of structures may not be reliable in practice, would also need to be addressed. As such, adding greater consistency and automation to the task of identifying, characterising and tracking construction components could aid their documentation and recovery during downstream activities, enabling their redistribution back into the supply chain.

During the last decades, a number of advanced "smart" technologies have emerged including radio frequency identification (RFID) tags, optical character recognition, 3D scanning laser, building information modelling (BIM), 3D computer-aided design (CAD), etc., becoming important tools in the construction sector (Ergen et al., 2007a; Majrouhi Sardroud, 2012). Among these technologies RFID - a wireless sensor technology operating based on the transmission of data via radio frequency (RF) signals to and/or from physical 'tags' attached to products and components (Dobkin, 2008; Domdouzis et al., 2007; Jaselskis and El-Misalami, 2003; Landt, 2005; Majrouhi Sardroud, 2012; Mennecke and Townsend, 2005; Sun et al., 2013; Valero et al., 2015; Yan, 2015) — stands out as one of the greatest contributing technologies of the 21st century. This is ascribed to its automatic data collection, information storage capability, ease of handling, durability and affordability (Hunt et al., 2007; Lim, 2012; Majrouhi Sardroud, 2012; Motamedi and Hammad, 2009).

There are currently three types of RFID tags available: passive; semi-passive; and active RFID tags (Cisco, 2014; Impinj, 2016; Sun et al., 2013; Valero et al., 2015). Active tags, due to owning their power source, have a greater read-write range (5–30m) than passive tags (read-write range of less than 2m long), but are more expensive than passive tags due to higher material and manufacturing costs (Kaur et al., 2011; Schindler et al., 2012). As such, active tags are usually applied in specialist areas where the higher costs and higher detail level of information stored are justified (e.g. in locating large assets). Passive tags due to their simplicity, adaptability and resistance to harsh environments have a vast number of generic applications in a variety of industries and sectors (Jaselskis and El-Misalami, 2003; Kaur et al., 2011; Schindler et al., 2012).

An additional advantage that has made RFID attractive is its ability to be integrated with a range of other technologies, maximising as such its potential to capture, transmit and collect data, providing business benefits and return on investments (CoreRFID, 2008; Valero et al., 2015). Depending on the task at hand, RFID can be integrated with geographic information system (GIS) and global positioning system (GPS) or ultrasound technologies (e.g. for locating materials and estimating their position in the construction site); personal digital assistant (PDA) technologies (e.g. for monitoring information such as material/component inventories and building drawings and other documentation and safety management); and BIM technologies (e.g. for storing and retrieving component lifecycle data and integrating those into new designs). BIM is a technology used to 'build' a structure in a digital environment, using virtual components, the characteristics and properties of which are analogous to the physical components available in the market which represent the physical and functional characteristics of a structure (Akbarnezhad et al., 2014; Bryde et al., 2013; Crotty, 2013; Sacks et al., 2010; Volk et al., 2014). The quantities and properties of the building components and materials used, as well as the building and component/product geometry, spatial relationships, geographic information, functionality etc., are typically embedded in BIM by the designers, owners and contractors, forming a useful database that is continuously updated (Akbarnezhad et al., 2014; Bryde et al., 2013). A unique RFID tag assigned to a construction component can be linked to a BIM database, enabling the recovery and organisation of its pertinent information during all building project phases. This can then be incorporated into a 3D information model. In that way reclaimed construction components can find their way in being reused into new structures in a much easier, cost-efficient and accurate way (Cheng and Chang, 2011; Motamedi and Hammad, 2009).

BIM's ability to digitally represent the physical and functional characteristics of a structure, and to retrieve data from a database, offers an effective way of modelling and managing this information in order to view, analyse and test the behaviour of a structure, while also permitting design changes to be made in a quick, effortless and reliable manner; forming a reliable basis for decision-making (Akbarnezhad et al., 2014; Cheng and Ma, 2011; Cheng and Chang, 2011; Crotty, 2013; Čuš-Babič et al., 2014; Ness et al., 2015; Sacks et al., 2010). There is now a suite of studies that demonstrate the feasibility of using BIM for streamlining whole-life performance of structures, from construction to EoL management (Akbarnezhad et al., 2014; Azhar et al., 2011; Volk et al., 2014); DfD interventions (Akinade et al., 2015, 2017); green building certification (Wong and Zhou, 2015); waste minimisation at the design and construction stage of a building (Akinade et al., 2015; Liu et al., 2015); all with the overarching aim of enabling an enhanced communication between the various stakeholders involved in modern construction projects in order to improve the environmental, economic and social performance of the construction industry (Arayici et al., 2011; Bryde et al., 2013; Costin et al., 2015; Sacks et al., 2009, 2010). However, the use of BIM to enable the reuse of construction components remains a niche.

Given the early-stage of RFID-BIM integration, this study is set on describing the role of RFID in storing, managing and supporting information flow through the construction components lifecycle, promoting their redistribution back to the supply chain. The prospect of integrating RFID with BIM for facilitating construction components reuse is explored as a means to enabling the construction sector to make the shift from a massive waste generator to a resource recovery implementer, streamlining the delivery of multiple benefits to the environment, economy and society. Additionally, a preliminary assessment of the strengths, weaknesses, opportunities and threats of the RFID technology is also presented in order to depict its current and future potential in sustainable construction components lifecycle management, and in capturing and possibly creating technical, environmental, economic and social value.

2. Using RFID for promoting sustainability in the construction sector via reuse

The application of RFID is particularly useful in the construction sector as it makes it possible to track and trace construction materials and components, equipment and tools, and even workforce, hence increasing the productivity and cost efficiency of construction projects (Cheng and Chang, 2011; Jaselskis and El-Misalami, 2003; Jaselskis et al., 1995; Jiang et al., 2011; Lee et al., 2013; Lu et al., 2011; Sun et al., 2013; Wing, 2006). RFID can also be used as a means of addressing the disconnect between upstream and downstream parts of the supply chain. This can be achieved by providing transparency and communication at the construction, maintenance and EoL phase of buildings and other structures. In aiding this, the designed physical and technical characteristics of construction components throughout their lifecycle - including information relevant to their manufacture, transportation, use, maintenance and disassembly - and their suitability to be reused, refurbished, remanufactured or recycled after the first, second or *n*-th cycle of its service life need to be communicated throughout their lifecycle. Section 2.1 describes the importance of retaining information flow in capturing all data associated with components' lifecycle, while Section 2.2 outlines the different types of information that need to be captured at each stage of the component's lifecycle, to ensure a sustainable lifecycle management. Finally in Section 2.3 the importance of managing this information for promoting construction components reuse through the use of RFID-BIM is highlighted.

2.1. *Information flow in promoting construction components reuse*

For retaining the functionality of a construction component, the information related to its treatment, use and maintenance would need to be updated throughout its entire lifecycle. This is because a component's life story would continue to evolve from its design towards its use, typical end-of-use (EoU), recovery and reuse, or EoL stage (Fig. 1). As such, changes to which the component is subjected during all phases of its lifecycle that can transform its characteristics and functionality, and hence its EoU, reuse and EoL fate have to be systematically monitored and updated (Ranasinghe et al., 2011; Terzi et al., 2010).

The idea that information on a component's lifecycle can be divided into different stages has also been reported in the study of Motamedi and Hammad (2009), who explained that this information should be stored at a suitable location enabling all stakeholders to efficiently access it, read it, and update it accordingly. Motamedi and Hammad (2009) also suggested that components to be tagged can be selected based on the scale of the project, types, and values of the components, the specific processes applied to these and the level of automation and management required by the owners. In this study, while the approach developed for capturing information throughout a components lifecycle is the same independently of the component's nature, we specifically promote it for tagging, tracking and updating the information relevant to structural (e.g. beams, columns) and semi-structural construction components (e.g. cladding, roofing) which are those that present a medium- to higher- reusability potential (Iacovidou and Purnell, 2016), due to their durability and resilience over time.

Updating the information stored in a component's RFID tag throughout its lifecycle is critical in generating the knowledge required for enabling its reuse. This knowledge can be used to provide confidence to designers and engineers that the suitability of a structural construction component to be reused in a new structure can be assessed not only on nominal properties, but the evolution of these properties with time (Akbarnezhad et al., 2014;

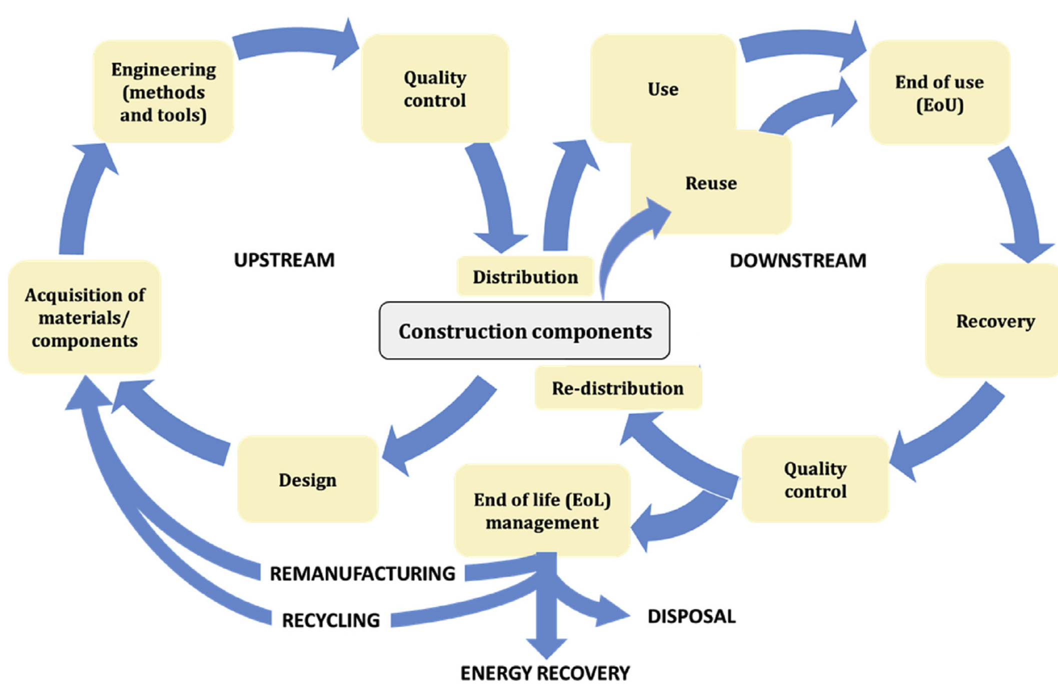

Fig. 1. The upstream and downstream circles of structural construction components lifecycle including EoU and EoL management options.

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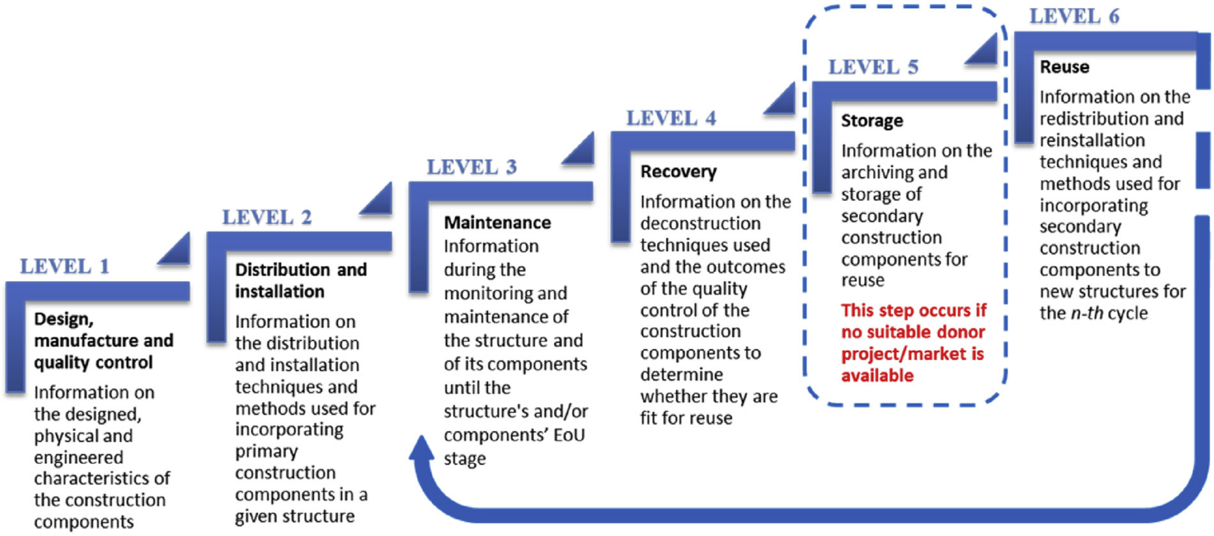

Fig. 2. Levels of information flow required for managing construction components reuse.

Motamedi and Hammad, 2009; Schultmann and Gollenbeck-Sunke, 2010). Some examples of important information that would be needed to assess its reuse potential include the:

- design date and place of manufacturer: changes in regulations with time may preclude (or encourage) the reuse of a particular component, and knowing the place of manufacture can help encourage the use of local products;
- life span in situ: this can be compared to the length of service the component has actually endured, giving a lower bound for nominal residual life;
- embodied carbon: this can be seen as a way of prioritising reuse of high embodied carbon components over others;
- loading history: this will determine if the component has been loaded within or in excess of its design loading envelope, affecting judgements regarding residual life;
- maximum bending moment and shear capacity: fundamental structural properties of an element that determine the suite of applications in which it might be used;
- connections and fixtures used: these will determine the ease with which a component can be removed from a structure with minimal damage, and how it can be incorporated into new structures;
- inspection results after deconstruction: this will alert designers to any possibility of defects arising during service, etc.

These are examples of key pieces of information that can and must be recorded on a component's RFID tag. This information may also be dynamically updated as attributes of that unique component into the BIM database, to enable its sustainable lifecycle management (a fuller list is given in Iacovidou and Purnell, 2016). The designers may then use the database to select and use salvaged components in new structures, based on their properties and availability, only by changing the design and layout of the designed structure and without risking its integrity (Akbarnezhad et al., 2014; Cheng and Chang, 2011; Ness et al., 2015). Moreover, the knowledge generated through the components' lifecycle may also provide the evidence required for promoting interventions in the design stage of future components (Fig. 1) oriented towards improving their performance, durability and recoverability, and as such the overall efficiency and sustainability in the construction sector.

Taking the above into consideration, it can be suggested that there are different levels of information that have to be taken into account for capturing components specificities in the most accurate manner. According to Fig. 1 six (6) levels of information could be distinguished (Fig. 2), providing a stepwise approach that gradually leads to building up the necessary information on structural components physical and technical properties and their changes over use, time and environment. This approach generates the knowledge required for a sound lifecycle evaluation and optimisation of their EoU (and eventually EoL) management. The use of RFID is considered to be a exceptionally value-added method of capturing this information over the construction assets long lifecycle.

However, for this technology to be successfully deployed and implemented, the co-operation of various actors along the supply chain and their consent to the use of RFID is especially required. This would ensure the systematical storage and update of structural construction components' information at all levels of their lifecycle (Kiritsis et al., 2003; Majrouhi Sardroud, 2012), supporting stakeholders at their respective role in promoting sustainability in the construction sector. This would in turn enable a vigorous transformation of the currently unsustainable practices into more effective and resourceful ones.

2.2. Typology of information required for promoting components reuse

The type of information that is to be stored in the RFID tags for promoting structural components' reuse - and sustainability overall - is perhaps one of the most important factors in certifying the successful uptake of this technology. This information can be divided into two categories:

- *Nominal information (static, essential):* this is the information that characterises the component in its as-installed state, analogous to that contained on the 'data sheet' traditionally issued by suppliers and delivered alongside the component; the supplier, the date of manufacture, size and weight etc. Referring to the proposed typology proposed in Iacovidou and Purnell (2016) and presented in Table 1, this would include the action of the component (i.e. its structural and/or functional role as installed), the material(s) from which it is made and grade(s) thereof, the installation method and connection type, and the type of

Table 1
Levels of information required for the typology of recovered structural components based on one and more service cycles.

Component Classifications[a]			Information Level	Information classification
1	Action	Physico-mechanical role of the component at deployment.	2, 3, 6	Static
2	Material	Grade and quality of materials used (especially for structural components) and recycled content.	1	Static
3	Deployment	Structure type in which the component was previously used.	2	Static
4	Exposure	Environmental conditions to which the component has been subjected.	2, 3, 5, 6	Dynamic
5	Loading	Physico-mechanical fate (e.g. loading history) of the component. For functional components, loadings might be expressed in other terms (e.g. electrical, traffic).	2, 3, 6	Dynamic
6	Recovery	Component handling and removal methods from the structure.	4	Static
7	Residual	Structural and functional properties of the component remaining (inspection at deconstruction site).	2, 3, 4, 5, 6	Dynamic
8	Connections	Capacity of the component to be connected to other structural and/or functional components and artefacts.	1, 2, 3, 4	Static
9	Availability	Details of when and where a component is likely to be available, and in what quantity based on generation and demand.	4,5,6	Dynamic
10	Regeneration	The number of service cycles of the component through reuse, and its thereafter upcycling, recycling or down-cycling/cascading.	1,2,3,4,5,6	Static/Dynamic

[a] Details on proposed components classifications can be found in Iacovidou and Purnell (2016).

structure in which it was deployed. It might also include inferred residual capacity information (i.e. how the component was expected to degrade with time in service) and information on the previous reuse history, if any. Environmental impact information such as embodied carbon, energy or water should also be included.

- *Service history information (dynamic, desirable):* this is information that evolves in response to the physical and environmental loads the component endures during its service lifetime. Again, referring to the typology of construction components, records of environmental conditions (temperature, humidity, chemical exposure etc.), loading history (stresses, strains, accidental damage), and further information allowing calculation of residual properties (e.g. evidence of corrosion, records from monitoring programs such as acoustic emissions) would allow much greater confidence in the reuse potential of the component, or conversely flag a component as being unfit for reuse and ready for recycling.

Further information would need to be added at the EoL stage. The techniques and procedures used to recover the component, any resultant impairments to components, particularly in regards to the state of the connections, etc. would need to be added on the tag, along with general inventory information such as storage location and conditions. It should also be possible for residual capacity measurements to be taken and thus the 'data sheet' for the component can be updated should dynamic service history information not be available. Table 1 lists the secondary component classifications suggested by Iacovidou and Purnell (2016) for developing a coherent and consistent classification system, presented herein alongside the levels of information required for each component classification and its nature (*static* or *dynamic*), as a guidance for capturing all the information relevant to the component for promoting its reuse.

The amount of data that can be stored on the tag *(static, essential information)*, the capability to modify the data on the tag after it has been initially programmed (*dynamic, desirable information*), and the lifetime of the tag to ensure its functionality over the components' lifecycle, are important aspects that must be taken into account (Domdouzis et al., 2007). *Static information* does not vary with time and as such is best suited to the use of passive RFID tags. On the contrary, *dynamic information* is addendum to the nominal information and as such is better suited to active RFID tags. This information could be gained from in-situ and/or ex-situ monitoring equipment. In the former case, RFIDs could share a power supply with these systems, whilst in the latter case, passive or semi-passive RFID tags would need to be updated at the same time as the monitoring event takes place. But as components may have different service lifecycles that range from 10 to over 50 years, it is important for the RFID tags attached to them to be able to function for longer periods than the common in other industries. These tags must also have long reading ranges and be attached to clearly defined locations in the component in order for them to be read. Some common rules and best practices about the location of the tag should be agreed upon, to guarantee the readability of tags and ease the reading process (Majrouhi Sardroud, 2012). In choosing the attachment method, the reusability of the RFID tags should also be taken into consideration. For instance, if the component is made of metal, the tag needs to be mounted approximately 1 cm from the metal surface to avoid interference (Valero et al., 2015). Further details on these topics are explored in the next section.

For new components used in new structures, the longer lifetime of the ultra-high frequency (UHF) passive tags, as well as their ability to retain important lifecycle information about component installation, use and maintenance, makes them a wiser choice over active tags. For components recovered from existing structures where RFID tags have not been previously used, active UHF RFID tags seem to be well-suited. This is especially the case when components are stored in salvage yards where long reading/detection distances are required in order to make the identification and selection of the desired components for reuse an informed and liable task (Ergen et al., 2007b). However active tags require their internal battery to be replaced approximately every 3–10 years, posing a real challenge when it comes to their selection for tracking and managing the lifecycle information of secondary construction components used in new structures (Kiziltas et al., 2008). Consequently, there will be a need for active tags to be replaced by UHF passive tags when the secondary structural components are installed into new structures in order to ensure their tracking, maintenance and recovery towards the structure's EoL stage. Nonetheless, having both active and passive tags in place can make the installation complex, and as such selection of only one type of RFID tags is considered prudent.

Technological innovation has shown that the lifetime of active UHF tags can be significantly improved by using energy harvesting devices that allow a significant reduction in the capacity of the on-board energy storage, while they incorporate additional features such as temperature sensing (De Donno et al., 2013; Janek et al., 2007). However, much research is still needed to assess their suitability for tagging products, including structural construction components. With improvements in the field of smart active labels (SALs), it is expected in the future that these tags are going to prevail due to their enhanced functionality and superior performance over existing passive labels (Schindler et al., 2012). Furthermore, advances that will enable sensor coupled RFID tags to monitor the impact of physical values (e.g. temperature, pressure, harmful agents: toxic chemicals, bacterial agents, etc.) on the structural components' performance, can be an innovative way to increase confidence in the properties of the components' and their potential reuse in new structures (Ness et al., 2015; Wing, 2006). However, research is still in its infancy.

2.3. Information lifecycle management via the use of RFID-BIM

RFID with its real-time information, visibility and traceability, can be integrated with BIM providing an innovative way for tracking and enhancing information management and communication throughout a component's lifecycle, minimising the time and labour needed for retrieving information related to a component and reducing the occurrence of ineffective decisions made due to the lack of information (Ergen et al., 2007b; Motamedi and Hammad, 2009). The detailed tracking and storaging of components lifecycle information via RFID, and the model of construction components in a structure and availability of information regarding their properties and characteristics (e.g. component type, material, size and weight, embodied carbon, recyclability and reusability, etc.) through BIM, can be a powerful aid for the determination of their reusability and recyclability potential (Akbarnezhad et al., 2014). The technical feasibility of integrating the two technologies was demonstrated in the study of Motamedi and Hammad (2009). These authors - using RFID tags on heating, ventilation and air conditioning (HVAC) equipment, and on fire equipment - have shown that the integration of the two technologies can be an effective tool for monitoring, inspection and the proper EoL management of these components (Motamedi and Hammad, 2009). Sattineni and Azhar (2010) have also shown that RFID-BIM technology can be useful in monitoring issues such as construction worker safety and productivity, as well as simply tracking the movement of materials and equipment on-site (Sattineni and Azhar, 2010).

Others have shown that combining RFID with BIM can help bridge the interface between BIM and a real project (Lu et al., 2011). By linking components' nominal information and history with the BIM platform database, it is possible to enhance the ability of BIM to collect actual and detailed (hazardous) material information, components' masses and connections, and other information relevant to maintenance and/or deconstruction planning, improving quality control, management and eventually the virtual sale of the components (Ness et al., 2015). This would then enable the physical relocation of components from one structure to another, and from use to reuse (Cheng and Chang, 2011; Ness et al., 2015; Volk et al., 2014). From the limited number of studies that have used RFID-BIM (Cheng and Chang, 2011; Motamedi and Hammad, 2009; Ness et al., 2015; Volk et al., 2014) to simplify the exchange of information and expertise between various parties during both the decision-making and constructive facility management phases projects, fewer still have been used to demonstrate its feasibility for promoting DfR interventions in the construction sector (Cheng and Chang, 2011; Ness et al., 2015).

Cheng and Chang (2011) have used RFID-BIM to enable the management of building components throughout the open-building lifecycle and promote building disassembly inferred from information stored on the RFID tags and integrated in the BIM platform followed by redesign and reuse. In the study of Ness et al. (2015), a scenario under which demountable steel structures and interior steel components tagged with RFID were salvaged from existing structures and were then added into the BIM database, was developed. Using this scenario, the authors showed that RFID-BIM can make it possible for these components to be virtually sold and imported into new BIM designs based on their remaining functionality and intended use, promoting as such resource efficiency in the construction sector, and achieving energy saving from reuse (Ness et al., 2015). They concluded that synchronisation of RFID-BIM on buildings that are about to be dismantled, tracking the components after they leave the site, and a detailed analysis and modelling based on specific components characteristics (e.g. energy, costs, embodied carbon, loading history) is needed and further research should be taken towards that direction.

Thereby, RFID-BIM has the potential to stimulate a new way of thinking in the construction sector, addressing key sustainability issues (Azhar et al., 2011; Krygiel and Nies, 2008). It can enable the better management of construction components due to its potential to reduce raw material use, wastage and carbon footprint via an informed recovery and reuse of construction components as mandated by a number or interventions such as deconstruction, DfR, DfD and DfMA (Akbarnezhad et al., 2014; Azhar et al., 2011; Costin et al., 2015; Krygiel and Nies, 2008); hence being an effective innovative disruption in the construction sector (Cheng and Chang, 2011; Motamedi and Hammad, 2009; Ness et al., 2015).

3. Opportunities and constraints in promoting reuse through RFID

3.1. Value creation via the use of RFID

At present, the recovery and reuse of construction components at the end of a structure's life is limited. This is attributed to the absence or inaccessibility of information about a structure's components and maintenance (e.g. material grade, material strength, properties, construction techniques used and the way components are connected with other components, maintenance cycles) that is crucially required by workers in order to properly recover components and direct them for reuse at the deconstruction stage. This has the implication of rendering deconstruction a time-consuming, labour-intensive and cost-inefficient process (Iacovidou and Purnell, 2016). Additionally, it lowers the level of reliability in the structural construction components properties and characteristics, necessitating an inspection process to certify component's quality and suitability for reuse. This procedure not only takes time and skilled workforce to be completed, but may also create a disruptive gap between deconstruction and reuse phase.

The evidence presented in this study suggests that RFID technology has the potential to bridge the gap between upstream and downstream parts of the structural construction components supply chain, and transform useful information about the components' properties, characteristics and performance, into valuable knowledge associated with components' lifecycle (Ameri and Dutta, 2005; Ergen et al., 2007b; Kiritsis et al., 2003; Motamedi and Hammad, 2009; Terzi et al., 2010). The rich knowledge stream that the RFID technology can deliver (as presented in the previous section), has the potential to boost the recovery and reuse of structural construction components, hence creating multiple values (Kiritsis et al., 2003; Schultmann and Gollenbeck-Sunke, 2010; Terzi et al., 2010). These values can be realised at multiple domains, as follows:

- *Technical*: Optimisation of the expected function of the component, improved handling and successful removal/installation of secondary components from/to the right location using the right hardware and connection material after exploiting the

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embedded data and information (e.g. material data, embodied carbon, production conditions, inspection results, installation, connections and joints used, and repairs conducted) stored in its RFID tag through its lifecycle; data accessibility up until component's EoL phase (Cheng and Chang, 2011; Ergen et al., 2007b; Kiritsis et al., 2003; Ness et al., 2015);

- *Economic:* Creation of economic value for the designer and contractor (e.g. green building achievement, lower costs and increased profit), the user (e.g. lower project costs), the salvage yard operators and distributors (e.g. new business opportunities with economic benefits), the component manufacturer (e.g. building reliability and preference, increasing profits through product preference and by repairing/refabricating existing ones, and minimising costs of production due to longer component life), and the waste managers (e.g. improved handling and recycling);
- *Environmental:* Reduction in carbon emissions, toxicity and the use of virgin resources by optimising the functionality of components through proper maintenance and end of their primary life planning (Ergen et al., 2007b; Kiritsis et al., 2003); improved waste management when components reach their EoL due to the inclusion of data useful in sustainable waste collection, management and disposal (Schindler et al., 2012);
- *Social:* Confidence over safety for the end user when salvaged components are used; improved welfare through the benefits generated by the reuse of construction components (Kiritsis et al., 2003); provision of valuable information about the behaviour of all stakeholders involved in the life story of a construction component (from its production to its final disposal), and waste management performance (Schindler et al., 2012).

While the uptake of RFID technology can offer multiple benefits via improving the lifecycle management of structural construction components, technical limitations can distort its real potential. The next section provides an overview of the potential limitations associated with the use of RFID over components lifecycle.

3.2. Limitations associated with the use of RFID

Reliability problems related to the location of tags, signal distortions due to dense reader set-up, and the material of the component to which the tags are adhered could severely affect the RFID performance (Lim et al., 2013; Valero et al., 2015; Wing, 2006). Metals (e.g. steel components), water/humidity and congestion in the environment (e.g. obstructing components) are known to cause radio signal interference that can influence the performance of the RFID by reducing the read range distance to one fifth and one half of the reading distance expected in open air (Ergen et al., 2007b; Kiziltas et al., 2008; Li and Becerik-Gerber, 2011; Lu et al., 2011).

To elaborate, in the study of Kiziltas et al. (2008) it was shown that for a tagged component placed underneath a ceiling panel and moderately surrounded by metal, the average reading distance was half of the original reading distance. For a component surrounded by metal and partially blocked by a wall, the average reading distance was 20–25% of the original distance (Kiziltas et al., 2008). This performance reduction may be caused via reflection or absorption of the radio signals by the objects in the environment. To minimize this effect, encapsulated tags are normally used (Ergen et al., 2007b; Kiziltas et al., 2008). In addition, in highly metallic and congested environments, multiple antennae can be used to ameliorate performance issues (Jaselskis and El-Misalami, 2003; Kiziltas et al., 2008). Furthermore, if there are electromagnetic sources working under a frequency similar to that of the system, special considerations should be made. To address interference limitations, new tags have been designed to be mounted on metallic objects, reaching a similar read range when mounted on metallic surfaces and working in free space (Valero et al., 2015).

Another limitation of RFID is in regards to the ability of its components (e.g., RFID readers, tags, hardware and software system) to work harmoniously and communicate effectively. Reading multiple times by the same reader in a short time-span (e.g., at entrance or exit gates) can result in a large data flow, that requires a fast system response in processing and filtering the data received, and transferring the necessary information to the related databases and applications such as BIM (Kiziltas et al., 2008). Moreover, identifying accurately the position of a component in a structure can sometimes be a challenging task, due to the similarity of components installed at the same space (Valero et al., 2015; Wing, 2006). The way components are fixed together in a structure can cause signal diminution which would reduce the tracking ability of a specific component. Tags location in a component and fixture methods used during construction may have to be reconsidered for enabling the use of RFID to become mainstream (Wing, 2006). The development of common RFID technical standards is currently restricting its development and uptake in the construction sector (Kaur et al., 2011). The low degree of standardization does not facilitate the proper use of RFID by the various actors in the supply chain withholding much of its potential (Kaur et al., 2011; Lu et al., 2011; Sun et al., 2013). The frequency ranges used for RFID in one country, are currently incompatible with those used in other countries. This broadens the gap between secondary components exchange and secondary markets development with a global appeal (Kaur et al., 2011; Lu et al., 2011).

Despite the aforementioned limitations, which with technological advances and policy development might be addressed in the future, an important factor that has to be taken into account when using RFID tags in structural components lifecycle management, is in regards to their disposal and recycling when they can no longer be functional. RFID tags and its contained materials pose a substantial threat to the recycling processes and/or the quality of the recyclates, as they contaminate the recyclates and prevents their effective processing into secondary resources with high technical value (Roussos and Kostakos, 2009; Schindler et al., 2012). RFID tags are complex objects composed of different organic and inorganic materials. Nowadays there is a variety of types of tags in different shapes and sizes. The main components of a conventional RFID tag are the antenna made of copper or aluminium (and silver for printed tags), the integrated circuit chip, made of silicon and gold (for bumps) and encapsulation made out of paper and plastic (i.e. polyethylene terephthalate (PET) and polypropylene (PP)) when adhesive tags are used, while in the case of active tags nickel batteries are also present (Schindler et al., 2012; WRAP, 2011). The tags can be between 10 and 40 cm^2 in size and weigh about 12–56 g, in the form of a flat square, which can be embedded in a plastic article during moulding, or adhered to its surface using polyurethane or acrylate. Although there are methods for separating RFID tags attached to components, some of them may be designed in such a way as to prevent it from being detached from the component. In those cases tags may end up in each of the construction components waste stream, significantly increasing the risk of compromising the quality of the recyclate due to contamination (Schindler et al., 2012). However, removal is possible, using a soluble adhesive and a wash stage before granulation, but it adds additional process complexity and thus not yet considered (WRAP, 2011). In addition there is no guarantee that the RFID tags will continue to operate after 20 years of use, but making certain that the information about a component's properties is captured periodically/ad hoc can provide some confidence over their use.

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The metals (e.g. copper, aluminium, nickel, gold, etc.) and plastic can be the sources of contamination expected from the RFID tags. For example, copper found in RFID tags can contaminate the steel making process and impair the quality of the steel elements. In Europe the limits of copper content in all grades of steel making is less than 0.5%, and although the copper found in the RFID tag can be in the range of 57 and 267 mg (depending on the tag dimensions), which is minimal compared to the tonnes of ferrous metals used in the conversion process, copper's cumulative nature over time may impair the quality of steel in the long-term (Das, 2009; Schindler et al., 2012). As opposed to copper, aluminium is oxidised during the melting process and transferred to the slag phase. Silicon is also transferred to the slag phase, whereas paper and plastic are burnt (Schindler et al., 2012). Similarly, in aluminium recycling, copper is an accumulating metal and unintentionally become an alloying element in the long-term that cannot be extracted, hence affecting aluminium quality (Schindler et al., 2012). In wood recycling, the tolerance in copper contamination is 40 mg/kg for recycled wood in panel board manufacture, and 200 mg/kg for recycled wood in both porous and non-porous surface applications (WRAP, 2012). The critical contaminant in wood recycling is plastic, as it cannot be removed affecting the end uses of the wood (e.g. biofuel) (WRAP,

Table 2
SWOT statement for the potential of RFID technology to enable structural construction components reuse.

	Strengths	Weaknesses
Direct	Identifies, locates and tracks components without human intervention[a-w] Stores and retrieves large volume of data at any time [c-f, k-n, q, u] Enables non line-of-sight scanning[b, c, f, i, j, m, n, u] Simultaneous reading of large volumes of data[c, f, i, m, n] Enhances tracking and forecasting of components performance[c, j, l, m] Increases reliability and accuracy[c, d, f, m] Robust and durable[c, d, f, i, j, m, u, v] Operates in harsh environments[c, d, f, m, n, v] Read-write ability and logging of lifecycle information[c, f, i, j, l-n, u] Reduces logistics in construction-deconstruction and reuse[f, m, n] Ability to test the condition of tags and assess their current status and remaining useful life[m] Can be combined with GPS, sensors and BIM technologies[c-e, i, l-n, q, u, v]	Signal diminution due to interference by metals, obstructing components and water[c, f, h, k, l, n, t, v,x] Signal collision increasing failure in detecting the position of a component in a structure[f, l, n, t, v, x] Reader ability affected by the thickness of substrate material on component surfaces, component material texture and oxidation on the RFID tag[f, m, n, u] Insufficient international RFID technical standards[f, l, n, s, v, x] Lack of integration across countries/continents on the standards regarding frequency range[f, l, v] Lack of a common platform for handling and exchanging data in different formats and across different stages of the supply chain[x] Cost restricting the development of RFID technology and its infrastructure[a, c, f, l-n, s-w] Tags vulnerability/failure over time[f, n, x]
	Opportunities	**Threats**
Indirect	Optimises the functionality of construction components[c, e, g, m, o, v] Improves handling/removal/installation of components for reuse[c, g, m, o] Enables data storage accessibility up until component's EoL phase[c, e, g, m, o, v] Creates economic value for all stakeholders involved in the construction sector[f] Reduces environmental impacts through reduction of components wastage and augmentation of their reuse[c, d, n] Empowers proper maintenance and end of primary life planning for construction components[c, f, n] Improves the collection and sorting of construction components at their EoL stage[n, r] Improves economic and social welfare through benefits generated by construction components reuse[g] Provides a great understanding of the behaviour of all stakeholders involved in the life story of a construction component and waste management performance[e, r] Enables communication between all stakeholders[e]	Lack of training and limited knowledge on the use and capabilities of the technology in the construction sector[m] Unwillingness to invest in RFID due to concerns about return on investmen[m, x] Risk of obsolescence of installed RFID solutions (e.g. declined reading performance ability)[x] Lack of unified standards and best of practice guidance[f, m, p, r] Environmental, economic and technical issues of existing and new tags in the recycling of wasted components[n, p, r] Lack of regulatory provisions for the recycling of RFID tags[y] Impact of existing and new design considerations on impairing communication between stakeholders and altering the benefits of new business models due to changes in information flow[p] Privacy and and security aspects around data sharing and open loop RFID solutions is often seen as a threat of industrial espionage[x, y]

[a] Cheng and Chang (2011).
[b] Costin et al., 2015.
[c] Ergen et al. (2007a,b).
[d] Jaselskis and El-Misalami (2003).
[e] Jun et al. (2009).
[f] Kaur et al. (2011).
[g] Kiritsis et al. (2003).
[h] Kiziltas et al. (2008).
[i] Ko (2009).
[j] Lee et al. (2013).
[k] Li and Becerik-Gerber (2011).
[l] Lu et al. (2011).
[m] Majrouhi Sardroud, (2012).
[n] Motamedi and Hammad (2009).
[o] Ness et al. (2015).
[p] Ngai et al. (2008).
[q] Ranasinghe et al. (2011).
[r] Schindler et al. (2012).
[s] Sun et al. (2013).
[t] Valero et al. (2015).
[u] Wang (2008).
[v] Wing (2006).
[w] Yan (2015).
[x] Lim et al. (2013).
[y] Roussos and Kostakos (2009).

2012). Flame retardants or pigments used in the tag's plastic layers, such as potassium or bromine, may also be carried into the recycling or disposal processes (Das, 2009; Schindler et al., 2012). Although, the amounts might be minimal, these might be critical in the environmental performance of the recycled components and as such, their fate has to be assessed. However, it is not the purpose of this paper to analyse the impact of RFID tags on the quality of the recyclates, but merely to provide an insight into the potential limitations that might occur when tags are introduced into the recycling processes. Impacts on quality can infer impacts on the economy, the environment and the society in general, and as such further research needs to be carried out in order to foresee any threats that might be imposed due to the use of RFID.

3.3. SWOT statement

An attempts to summarise the strengths and weaknesses of RFID, and provide an insight into the short-, medium- and long-term opportunities that can be created through its use and potential threats that might hinder this technology from becoming a widespread tool, has been made (Table 2).

The SWOT statement presented in Table 2 indicates that there is a need to address the threats and weaknesses of RFID, for its full potential to be unlocked. Thereby, there is a need to gain a better understanding of where innovation and deployment investments in the RFID technology are likely to return the greatest advantages. These can not only provide the right opportunities in technical and economic terms, but also in environmental and social. Policies that regulate the use and management of RFID tags do not currently exist. Nonetheless, a protocol for removing RFID tags prior to recycling is needed. The reason for this is twofold; first to ensure that the quality of the materials recovered for recycling remains high, and second to safeguard that the RFID uptake for promoting structural construction components reuse is not compromised by the inability of RFID tags to be detached from them at them EoL stage. Likewise, it is important to ensure that the technological advances made in this field (i.e. to deal with RFID's limitations, etc.) are not debilitated by immature legislation enforcement, or specifications development (Schindler et al., 2012).

Finally, awareness is key; stakeholders involved at the various stages of the construction supply chain from RFID designers to waste managers, must be made aware of the potential of RFID in controlling and managing resources at all stages of construction-deconstruction-reuse-disposal. They must also be trained how to properly use this technology in order to ensure full realisation of its benefits. Once RFID and RFID–BIM technologies become established, it should become a prerequisite for all designers and construction companies to incorporate them into their practices. This would enable them to properly assess the technical and economic feasibility of new approaches with a focus on sustainability, maximising the multiple benefits that such approaches can offer. Overall, by:

- achieving improved communication between all the stakeholders involved;
- maintaining the information flow through the various levels of construction-deconstruction-reuse; and
- demonstrating commitment to improving awareness and sustainability in the construction sector,

potential uptake of the RFID technology is likely to grow. This is almost be certain when technological innovations provide solutions to RFID's current limitations, and sustainability issues become ever more pressing.

4. Conclusions

A prerequisite when dealing with construction components management, is to understand how their characteristics and functionality are transformed at each step of their lifecycle. This information if properly recovered and stored can be a valuable tool in promoting structural components' recovery and reuse. RFID is clearly an efficient technology for capturing and retaining this information flow in a sustainable fashion. This is ascribed to its capacity to store, transfer and access a relatively large number of data, as well as its potential to be integrated with a range of other technologies that maximise its capabilities. RFID's combination with BIM is aspired to be one of the most important technological innovations in the construction sector due to its capability to track, locate, read/write, update and retrieve and store components' lifecycle information into a database, which may add new capabilities to the design of new, sustainable structures. Yet, the development and successful application of the RFID-BIM technology, is still a niche. Nonetheless, RFID can be used as a standalone technology aiding not only the reuse and sustainable lifecycle management of construction components, but also the efficient communication between all stakeholders involved in the construction supply chain. Tag designers would have, for the first time, a common line of communication with CDW managers that would support the refinement of the performance of both the construction and waste management sectors. Furthermore, the widespread uptake of RFID in the construction sector can create the right setting for new business models to flourish, carrying the potential to unlock multiple technical, environmental, economic, and social benefits. For all the above to be achieved full utilisation of the capacity of the RFID technology has to be accomplished. With technological advances providing the means to solve RFID's technical limitations and further enhance its abilities by incorporating additional features such as GPS and sensor technologies; and with policy development enabling its control and sustainable management at all stages of the supply chain, its mainstream use as a structural construction components reuse enabler might soon become realised.

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References

Akbarnezhad, A., Ong, K.C.G., Chandra, L.R., 2014. Economic and environmental assessment of deconstruction strategies using building information modeling. Automat. Constr. 37, 131–144.

Akinade, O.O., Oyedele, L.O., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A., Bello, S.A., 2015. Waste minimisation through deconstruction: a BIM based deconstructability assessment score (BIM-DAS). Resour. Conservation Recycl. 105, Part A 167–176.

Akinade, O.O., Oyedele, L.O., Omoteso, K., Ajayi, S.O., Bilal, M., Owolabi, H.A., Alaka, H.A., Ayris, L., Henry Looney, J., 2017. BIM-based deconstruction tool: towards essential functionalities. Int. J. Sustain. Built Environ. press.

Ameri, F., Dutta, D., 2005. Product lifecycle management: closing the knowledge loops. Comput. Aid. Des. Appl. 2, 577–590.

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C., O'Reilly, K., 2011. BIM adoption and implementation for architectural practices. Struct. Surv. 29, 7–25.

Azhar, S., Carlton, W.A., Olsen, D., Ahmad, I., 2011. Building information modeling for sustainable design and LEED® rating analysis. Automat. Constr. 20, 217–224.

BIO Intelligence Service, 2011. Service Constract on Management of Construction and Demolition Waste - SR1. European Commission (DG ENV) Framework

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contract ENV.G.4/FRA/2008/0112, Paris, France. Final Report Task 2.
Bryde, D., Broquetas, M., Volm, J.M., 2013. The project benefits of building information modelling (BIM). Int. J. Proj. Manag. 31, 971–980.
Cheng, J.C.P., Ma, L.Y.H., 2011. RFID supported cooperation for construction waste management. In: Luo, Y. (Ed.), Cooperative Design, Visualization, and Engineering: 8th International Conference, CDVE 2011, Hong Kong, China, September 11-14, 2011. Proceedings. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 125–128.
Cheng, M.-Y., Chang, N.-W., 2011. Radio frequency identification (RFID) integrated with building information model (BIM) for open-building life cycle information management. In: 28th International Symposium on Automation and Robotics in Construction and Mining (ISARC), Seoul, Korea, pp. 485–490.
Cisco, 2014. RFID Tag Considerations, Wi-fi Location-based Services 4.1 Design Guide.
CoreRFID, 2008. A White Paper on RFID Technology in the Construction Industry Construction & RFID. The ROI. CoreRFID Ltd., Warrington DC.
Costin, A.M., Teizer, J., Schoner, B., 2015. RFID and BIM-enabled worker location tracking to support real-time building protocol and data visualization. ITcon 20, 495–517.
Crotty, R., 2013. The Impact of Building Information Modelling: Transforming Construction. Routledge.
Čuš-Babič, N., Rebolj, D., Nekrep-Perc, M., Podbreznik, P., 2014. Supply-chain transparency within industrialized construction projects. Comput. Ind. 65, 345–353.
Das, R., 2009. How Green is RFID?, e-FlexoGlobal.
De Donno, D., Catarinucci, L., Tarricone, L., 2013. An UHF RFID energy-harvesting system enhanced by a DC-DC charge pump in silicon-on-insulator technology. IEEE Microw. Wirel. Components Lett. 23, 315–317.
Dobkin, D.M., 2008. Chapter 2-history and practice of RFID. The RF in RFID. Newnes, Burlington, pp. 7–49.
Domdouzis, K., Kumar, B., Anumba, C., 2007. Radio-Frequency Identification (RFID) applications: a brief introduction. Adv. Eng. Inf. 21, 350–355.
Ergen, E., Akinci, B., East, B., Kirby, J., 2007a. Tracking components and maintenance history within a facility utilizing radio frequency identification technology. J. Comput. Civ. Eng. 21, 11–20.
Ergen, E., Akinci, B., Sacks, R., 2007b. Life-cycle data management of engineered-to-order components using radio frequency identification. Adv. Eng. Inf. 21, 356–366.
European Commission, 2016a. Construction and Demolition Waste (CDW), ENVIRONMENT. Waste, European Commission.
European Commission, 2016b. Resource efficient use of mixed wastes. In: European Commission, E., Waste (Eds.), Studies.
Hunt, V.D., Puglia, A., Puglia, M., 2007. RFID: a Guide to Radio Frequency Identification. John Wiley & Sons.
Iacovidou, E., Purnell, P., 2016. Mining the physical infrastructure: opportunities, barriers and interventions in promoting structural components reuse. Sci. Total Environ. 557–558, 791–807.
Impinj, 2016. Chapter 3: the Different Types of RFID Systems RFID Technology Primer. Impinj, Inc.
Janek, A., Steger, C., Preishuber-Pfluegl, J., Pistauer, M., 2007. In: Lifetime Extension of Higher Class UHF RFID Tags Using Special Power Management Techniques and Energy Harvesting Devices, Dagstuhl Seminar Proceedings.
Jaselskis, E., El-Misalami, T., 2003. Implementing radio frequency identification in the construction process. J. Constr. Eng. Manag. 129, 680–688.
Jaselskis, E.J., Anderson, M.R., Jahren, C.T., Rodriguez, Y., Njos, S., 1995. Radio-frequency identification applications in construction industry. J. Constr. Eng. Manag. 121, 189–196.
Jiang, S., Skibniewski, M.J., Yuan, Y., Sun, C., Lu, Y., 2011. Ultra-wide band applications in industry: a critical review. J. Civ. Eng. Manag. 17, 437–444.
Jun, H.B., et al., 2009. A framework for RFID applications in product lifecycle management. Int. J. Comput. Integr. Manuf. 22 (7), p. 595–615.
Kaur, M., Sandhu, M., Mohan, N., Sandhu, P.S., 2011. RFID technology principles, advantages, limitations & its applications. Int. J. Comput. Electr. Eng. 3, 1793–8163.
Kiritsis, D., Bufardi, A., Xirouchakis, P., 2003. Research issues on product lifecycle management and information tracking using smart embedded systems. Adv. Eng. Inf. 17, 189–202.
Kiziltas, S., Akinci, B., Ergen, E., Tang, P., 2008. Technological assessment and process implications of field data capture technologies for construction and facility/infrastructure management. ITcon 13, 134–154.
Ko, C.-H., 2009. RFID-based building maintenance system. Automat. Constr. 18 (3), p. 275–284.
Krygiel, E., Nies, B., 2008. Green BIM: Successful Sustainable Design with Building Information Modeling. John Wiley & Sons.
Landt, J., 2005. The history of RFID. IEEE Potentials 24, 8–11.
Lee, J.H., Song, J.H., Oh, K.S., Gu, N., 2013. Information lifecycle management with RFID for material control on construction sites. Adv. Eng. Inf. 27, 108–119.
Li, N., Becerik-Gerber, B., 2011. Life-cycle approach for implementing RFID technology in construction: learning from academic and industry use cases. J. Constr. Eng. Manag. 137, 1089–1098.
Lim, M.K., 2012. Exploring value-added benefits to enhance wider adoption of chipless RFID system. In: Karmakar, N.C. (Ed.), Advanced RFID Systems, Security, and Applications. IGI Global, Hershley, PA (US).
Lim, M.K., Bahr, W., Leung, S.C.H., 2013. RFID in the warehouse: a literature analysis (1995–2010) of its applications, benefits, challenges and future trends. Int. J. Prod. Econ. 145, 409–430.
Liu, Z., Osmani, M., Demian, P., Baldwin, A., 2015. A BIM-aided construction waste minimisation framework. Automat. Constr. 59, 1–23.
Lu, W., Huang, G.Q., Li, H., 2011. Scenarios for applying RFID technology in construction project management. Automat. Constr. 20, 101–106.
Majrouhi Sardroud, J., 2012. Influence of RFID technology on automated management of construction materials and components. Sci. Iran. 19, 381–392.
Mennecke, B.E., Townsend, A.M., 2005. Radio Frequency Identification Tagging as a Mechanism of Creating a Viable Producer's Brand in the Cattle Industry. MATRIC Research Papers.
Motamedi, A., Hammad, A., 2009. Lifecycle management of facilities components using radio frequency identification and building information model. ITcon 14, 238–262.
Ness, D., Swift, J., Ranasinghe, D.C., Xing, K., Soebarto, V., 2015. Smart steel: new paradigms for the reuse of steel enabled by digital tracking and modelling. J. Clean. Prod. 98, 292–303.
Ngai, E.W.T., et al., 2008. RFID research: An academic literature review (1995–2005) and future research directions. Int. J. Prod. Econ. 112 (2), p. 510–520.
Ranasinghe, D.C., Harrison, M., Främling, K., McFarlane, D., 2011. Enabling through life product-instance management: solutions and challenges. J. Netw. Comput. Appl. 34, 1015–1031.
Roussos, G., Kostakos, V., 2009. RFID in pervasive computing: state-of-the-art and outlook. Pervasive Mob. Comput. 5, 110–131.
Sacks, R., Dave, B., Koskela, L., Owen, R., 2009. Analysis Framework for the Interaction between Lean Construction and Building Information Modelling.
Sacks, R., Koskela, L., Dave, B., Owen, R., 2010. Interaction of lean and building information modeling in construction. J. Constr. Eng. Manag. 136, 968–980.
Sattineni, A., Azhar, S., 2010. Techniques for tracking RFID tags in a BIM model. In: 27th International Symposium on Automation Ad Robotics in Construction (ISARC), June 25-27, 2010, Bratislava, Slovakia.
Schindler, H.R., Schmalbein, N., Steltenkamp, V., Cave, J., Wens, B., Anhalt, A., 2012. In: Commission (Ed.), SMART TRASH: Study on RFID Tags and the Recycling Industry. RAND Corporation, Santa Monica, CA.
Schultmann, F., Gollenbeck-Sunke, N., 2010. The contribution of RFID to life cycle management in construction. In: Industrialised, Integrated, Intelligent Sustainable Construction, vol. 149.
Sun, C., Jiang, F., Jiang, S., 2013. Research on RFID applications in construction industry. J. Netw. 8, 1221–1228.
Terzi, S., Bouras, A., Dutta, D., Garetti, M., Kiritsis, D., 2010. Product lifecycle management – from its history to its new role. Int. J. Prod. Lifecycle Manag. 4, 360–389.
Valero, E., Adán, A., Cerrada, C., 2015. Evolution of RFID applications in construction: a literature review. Sensors (Basel, Switz. 15, 15988–16008.
Volk, R., Stengel, J., Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings – literature review and future needs. Automat. Constr. 38, 109–127.
Wang, L.-C., 2008. Enhancing construction quality inspection and management using RFID technology. Automat. Constr. 17 (4), p. 467–479.
Wing, R., 2006. RFID applications in construction and facilities management. J. Inf. Technol. Constr. (ITcon) 11, 711–721.
Wong, J.K.W., Zhou, J., 2015. Enhancing environmental sustainability over building life cycles through green BIM: a review. Automat. Constr. 57, 156–165.
WRAP, 2011. Development of NIR Detectable Black Plastic Packaging Waste & Resources Action Programme, Banbury, UK.
WRAP, 2012. PAS 111:2012–Specifi Cation for the Requirements and Test Methods for Processing Waste Wood. Waste & Resources Action Programme, Banbury, UK.
Yan, Q., 2015. Research on fresh produce food cold chain logistics tracking system based on RFID. Adv. J. Food Sci. Technol. 7, 191–194.

Please cite this article in press as: Iacovidou, E., et al., The use of smart technologies in enabling construction components reuse: A viable method or a problem creating solution?, Journal of Environmental Management (2017), http://dx.doi.org/10.1016/j.jenvman.2017.04.093